New Series Resonance Type Fault Current Limiter

M. Tarafdar Hagh, M. Jafari, S. B. Naderi

***Abstract*--This paper proposes a new topology for fault current limiter (FCL) that is based on series LC resonance circuit. The proposed FCL uses a high speed switch to put an inductor in series with a capacitor and make resonance condition between them. This structure can hold the peak of fault current in the constant value that is not possible in previously introduced series resonance type FCLs. In such conditions, if fault continues, power system will not be experience large short circuit currents. Using non-superconducting inductor instead of superconducting one, leads to low construction and maintenance costs in this structure. In addition, in normal operation, capacitor of this FCL can be used as a series compensator. Analytical analysis for the proposed series resonance type FCL is performed in detail. Simulations are presented using PSCAD/EMTDC software to show the operation of the proposed FCL. Also, comparison between the proposed FCL and previous series resonance type FCLs is included in simulations.**

***Keywords*: fault current limiter, series resonance, non-superconducting inductor, arrester, self turn off switch.**

I. Introduction

NOWADAYS, with the trend of growing electric power systems and their interconnections, fault current levels are increased and these fault levels may exceed the current rating of system equipments. In this condition, the realization of a fault current limiter (FCL) is going to be expected strongly. FCL structures not only are used for effective suppression of faults in power system, but also are applied to variety of applications such as power quality and transient stability improvement. Many types of FCLs are introduced in literature, such as superconducting FCLs (resistive or inductive types), solid state FCLs, flux-lock type FCLs and resonance type FCLs [1-8].

Previously presented resonance type FCLs are used a capacitor in series or parallel with superconducting inductors and limited fault currents by this way [9-12]. However, these structures have two problems. Firstly, because of high technology and costs (construction and maintenance costs) of superconductors, there are not commercially available. Secondly, by using these structures, peak of current is not constant during the fault and has increasing variation. So, for the faults that last more time, it may be harmful for utility equipments, even considering high speed breakers. In addition, by increasing manner of fault current, selecting the power rating of breakers will be a problem.

In this paper a new series resonance type FCL is introduced. Using non-superconducting inductor in this topology leads to low construction and maintenance costs. Also, by the proposed FCL, fault current's peak will be constant. In addition, capacitor of this structure can be used as series compensator in normal operation, that it is not possible in previously introduced series resonance type FCLs; because, in those structures inductor and capacitor are in resonance condition in normal operation of power system. Analytical analysis is performed and simulations are presented using PSCAD/EMTDC software to show the effectiveness of this structure.

II. Power Circuit Topology of the Proposed FCL and Principles of Operation

Fig. 1 shows single phase power circuit topology of the proposed FCL. It is necessary to use a similar circuit for each phase in a three-phase power system. This structure is composed of two main parts which are described as follows:

1) Bridge part: This part consists of a semi-conductor rectifier (SCR) bridge containing D_1 to D_4 diodes, a small dc limiting reactor (L_{dc}), a self turn off switch (such as GTO, IGBT, etc) and a free wheeling diode (D_f).

2) Resonance part: This part consists of a series LC resonant circuit (L_{sh} and C) that is tuned on 50 Hz network frequency and an arrester in parallel with the capacitor. Note that the natural resistance of inductor (R_{sh}) is considered too.

Bridge part of FCL operates as a high speed switch that changes the fault current path to resonance part, when fault occurs. Obviously, as a conventional method, it is possible to substitute this part with an anti parallel connection of two semiconductor switches. In this case, it is necessary to use a series inductor with each switch for limiting the di/dt. These inductors make a voltage drop on FCL in normal operation of power system. But, using diode rectifier bridge and placing a self turn off switch inside the bridge has two advantages compared to two anti-parallel switches as follows:

1) This structure uses only one controllable semiconductor device which operates at dc side, instead of two switches that

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Paper submitted to the International Conference on Power Systems Transients (IPST2011) in Delft, the Netherlands June 14-17, 2011

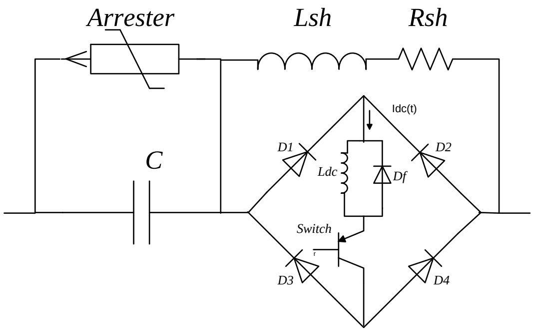

Fig. 1. Power circuit topology of the proposed FCL

operate at ac current. So, control circuit is simpler because of no need to switching ON/OFF at normal operation case. In addition, there is not switching losses.

2) It is possible to placing a small reactor in series with the self turn off switch at dc side. This reactor plays two roles; Snubber for self turn off switch to protect it and current limiter at first moments of fault that will be discussed in detail.

In normal operation of power system, self turn off switch is ON and small dc reactor is charged to the peak of line current and behaves as short circuit. Neglecting small voltage drop on diodes and self turn off switch, total voltage drop on FCL becomes almost zero and therefore, FCL does not affect normal operation of power system. As fault occurs, dc reactor limits increasing rate of short circuit current and starts to charge. When the line current reaches to the pre-defined value that can be set by system operator, control system turns off the self turn off switch. So, the bridge retreats from utility. At this moment, free wheeling diode turns on and provides free path for discharging the dc reactor. When the bridge turns off, fault current passes through the resonance part of the proposed FCL.

Without using arrester in the proposed topology, only series LC resonance circuit will be in fault current path. As will be shown in analytical analysis section, in such condition, fault current will has increasing variations. But, by using arrester, fault current can be limited to a constant value. In addition, it is possible to protect the capacitor from over voltages that can be harmful.

By removal of fault, self turn off switch turns on again and system returns to the normal state.

Some previous structures have AC power losses in resonant circuit during no-fault condition, because of placing large inductor in line current path [11, 12]. But, this structure has very lower losses at normal condition. Total power loss of the proposed structure is made by semiconducting devices and small resistance of dc reactor. It is very small percentage of the transmitted power of feeder and can be ignored for most of practical applications [13].

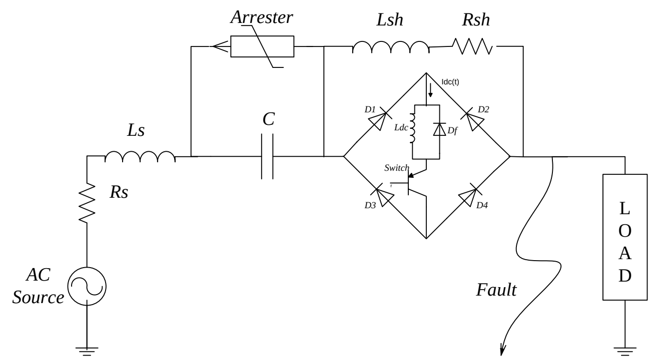

Fig. 2. Power system with the proposed FCL

III. Analytical Analysis of the Proposed Structure

Power system of Fig. 2 is used as a power system with the proposed FCL to perform analytical analysis and simulations.

Study on operation of the proposed FCL during fault is presented in three modes as follow:

Mode I: fault occurrence instant, t_f to self turn off switch operation, t_0;

Mode II: self turn off switch operation to arrester conduction instant, t_1;

Mode III: arrester conduction interval (t_1 to t_2).

A. Mode 1 (from t_f to t_0 in Fig. 3)

As mentioned in section II, in normal operation state, self turn off switch is ON and the proposed FCL has no effect on power system operation. When a short circuit occurs at t_f, the dc limiting reactor can limit the increasing rate of fault current. The self turn off switch doesn't operate until the line current reaches to a per-defined value (I_0). Since, time interval of fault occurrence instant to self turn off switch operation is very small, its analysis is not presented in detail in this paper.

B. Mode 2 (from t_0 to t_1 in Fig. 3)

The value of line current reaches to I_0 and self turn off switch turns off at this moment, t_0. Initial current value of shunt inductance and source inductance are zero and I_0, respectively. So, to calculate initial current value (I_{eq0}) for the equivalent inductance (L), Eq. (1) is used as follow:

$$I_{eq0} = I_0 \sqrt{\frac{L_s}{L_s + L_{sh}}} \tag{1}$$

In this condition, differential equation of line current ($i(\omega t)$), can be expressed by Eq. (2).

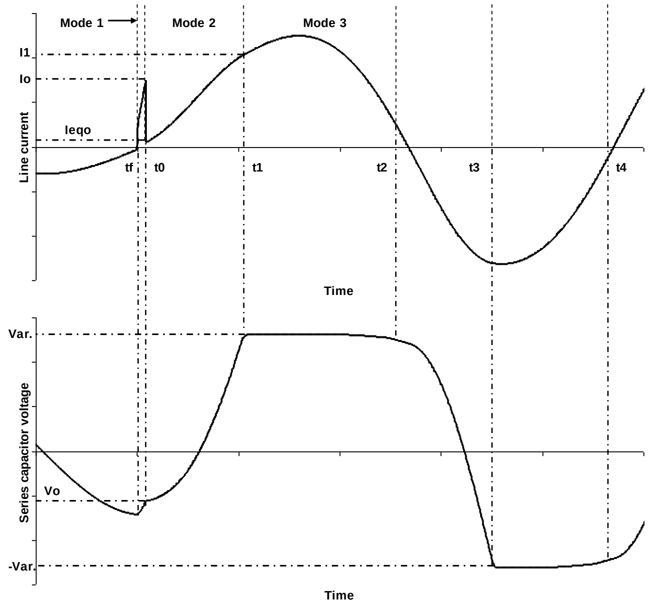

Fig. 3. Operation modes of the proposed FCL

$$\begin{cases} \dfrac{di^2(\omega t)}{d\omega t^2}+\dfrac{R}{L\omega}\dfrac{di(\omega t)}{d\omega t}+\dfrac{1}{LC\omega^2}i(\omega t) \\ =\dfrac{v_m}{L\omega}\cos(\omega t)+\dfrac{I_{eq0}}{LC\omega^2} \\ i(\omega t=\omega t_0)=I_{eq0} \\ \dfrac{di(\omega t=\omega t_0)}{d\omega t}=\dfrac{v_m\sin(\omega t_0)-RI_{eq0}-v_0}{L\omega}=I_0' \end{cases} \tag{2}$$

where, $R=R_{sh}+R_s$, $L=L_{sh}+L_s$.

So, equation of $i(\omega t)$ can be derived as follow:

$$\begin{aligned} i(\omega t)=&e^{A\omega(t-t_0)}\left(k_1\cos(B\omega(t-t_0))+k_2\sin(B\omega(t-t_0))\right) \\ &+k_3\sin(\omega t)+k_4\cos(\omega t)+k_5 \end{aligned} \tag{3}$$

where:

$$A=-\frac{R}{2L\omega},\ B=\sqrt{\frac{4}{LC\omega^2}-\frac{R^2}{L^2\omega^2}} \tag{4}$$

and:

$$\begin{cases} k_1=-k_3\sin(\omega t_0)-k_4\cos(\omega t_0) \\ k_2=\dfrac{I_0'-Ak_1-k_3\cos(\omega t_0)+k_4\sin(\omega t_0)}{B} \\ k_3=\dfrac{\dfrac{R}{L\omega}\dfrac{v_m}{L\omega}}{\dfrac{R^2}{L^2\omega^2}+\left(\dfrac{1}{LC\omega^2}-1\right)^2},k_4=\dfrac{\left(\dfrac{1}{LC\omega^2}-1\right)\dfrac{v_m}{L\omega}}{\dfrac{R^2}{L^2\omega^2}+\left(\dfrac{1}{LC\omega^2}-1\right)^2} \\ k_5=I_{eq0} \end{cases} \tag{5}$$

In addition, the initial voltage of series capacitor is considered v_0 at t_0.

We know that the inductance of source is negligible in comparison with the L_{sh}. So, L and C are in resonance. If the fault lasts several cycles, $i(\omega t)$ will tend Eq. (6), approximately (considering Eq. (3)).

$$i(\omega t)=\frac{v_m}{R}\sin(\omega t)+I_{eq0} \tag{6}$$

It is true that presence of L and C limit increasing rate of line current in fault condition, but it is not suitable for faults that last more time. In following discussion, it will be shown that using arrester in parallel with the series capacitor can prevent the increasing variation of fault current.

C. Mode 3 (from t_1 to t_2 in Fig. 3)

When the series capacitor voltage reaches to arrester voltage rating ($V_{ar.}$) at t_1, it is clamped to $V_{ar.}$. In this state we have:

$$\begin{cases} \dfrac{di(\omega t)}{d\omega t}+\dfrac{R}{L\omega}i(\omega t)=\dfrac{v_m}{L\omega}\sin(\omega t)-\dfrac{V_{ar.}}{L\omega} \\ i(\omega t=\omega t_1)=I_1 \end{cases} \tag{7}$$

Solving Eq. (7) results line current equation in arrester operation interval. So we have:

$$\begin{cases} i(\omega t)=k_1e^{-\frac{R}{L\omega}\omega(t-t_1)}+\dfrac{v_m}{R^2+L^2\omega^2}\sin(\omega t-\varphi)-\dfrac{V_{ar.}}{R} \\ k_1=I_1+\dfrac{V_{ar.}}{R}-\dfrac{v_m}{R^2+L^2\omega^2}\sin(\omega t_1-\varphi) \\ \varphi=\arctan(\dfrac{L\omega}{R}) \end{cases} \tag{8}$$

Equation (8) shows that if the fault takes several cycles, arrester prevents increasing state of line current. The mode of operation from t_2 to t_3, is similar to mode 2, but initial values for series capacitor and inductance are different. There are similar conditions on $[t_3,t_4]$ interval and mode 3.

Presented analysis shows that by selecting proper values for L_{sh} and C and $V_{ar.}$ (see Eq. (3) and (8)), it is possible to control the fault current level in desired value. For high voltage levels, these values should be changed due to required high limiting impedance. Also, semiconducting devices should be chosen from available high rating devices [14].

IV. SIMULATION RESULTS

Power circuit topology of Fig. 2 is used for simulation at fault condition. Simulation parameters are as Table I.

Fault occurs at $t_f=1s$ and continues four cycles of power system frequency, $0.08s$. When fault happens, the line current increases sharply without using the proposed FCL. Fig. 4 shows line current in this state.

By using the proposed structure, before operation of self turn off switch, L_{dc} limits the increasing rate of fault current. When the fault current reaches to pre-defined value ($I_o = 150A$), self turn off switch turns off and fault current is limited by resonance circuit to acceptable value (Fig. 5).

Fig. 6 shows the arrester current. Conduction intervals of arrester are clear in this figure. Current of L_{sh} is shown in Fig. 7. Its current is equal to line current during fault and zero for no-fault conditions.

Fig. 8 shows the series capacitor voltage. Considering Fig. 8, it is obvious that arrester clamps capacitor voltage and protects it from over voltage conditions.

To show the effectivness of using arrester, the line current and series capacitor voltage without using arrester in the proposed structure are shown in Fig. 9 and 10 in fault condition. Fig 9 and 10 show that if fault lasts several cycles, the line current and capacitor voltage increase to large values that may damage the capacitor and other equipments of power system or put them in stress.

Table I: Simulation parameters

Source parameters		$V_s = 6.6\sin(\omega t)kV, L-G, RMS, \omega = 2\pi f;$ $f = 50Hz, R_s = 0.5\Omega, L_s = 4mH;$
Parameters of the proposed FCL	Resonant circuit	$C = 68\mu F, L_{sh} = 150mH, R_{sh} = 0.4\Omega;$ $V_{ar.} = 5kV,\ peak;$
	dc side	$L_{dc} = 10mH;\ V_{DF} = V_{DIGBT} = 3V;$
Load parameters		$R_L = 150\Omega, L_L = 200mH.$

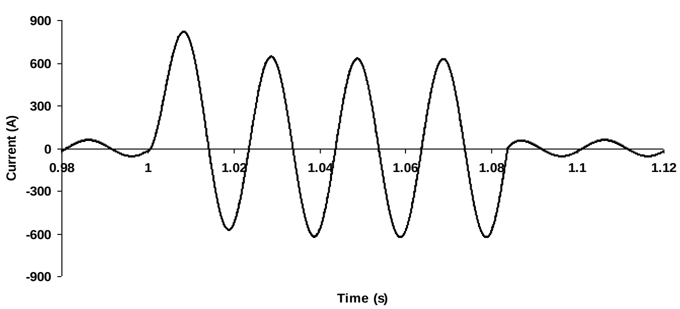

Fig. 4. Line current without the proposed FCL

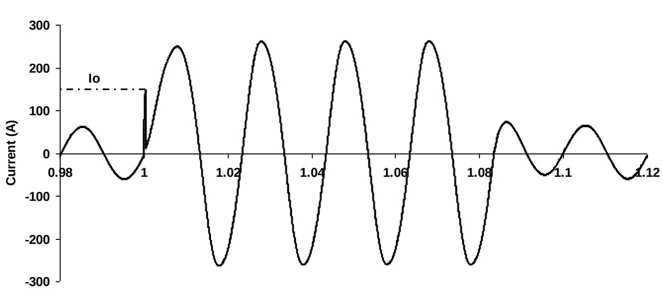

Fig. 5. Line current with the proposed FCL

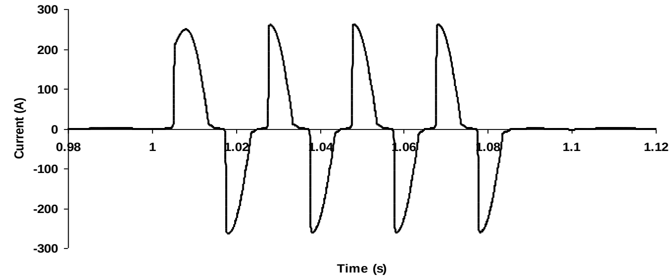

Fig. 6. Arrester current

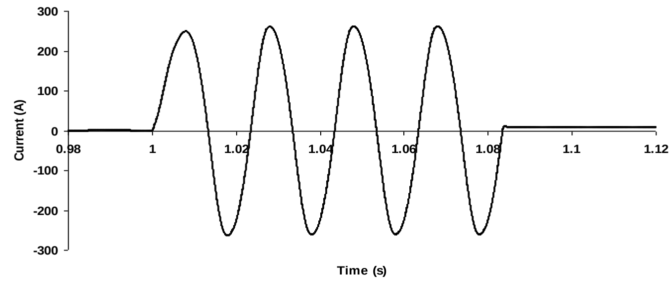

Fig. 7. L_{sh} current

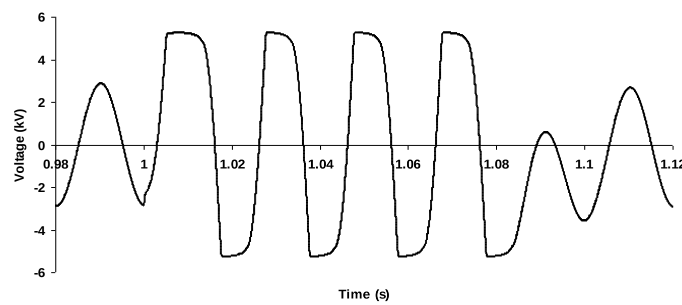

Fig. 8. Series capacitor voltage

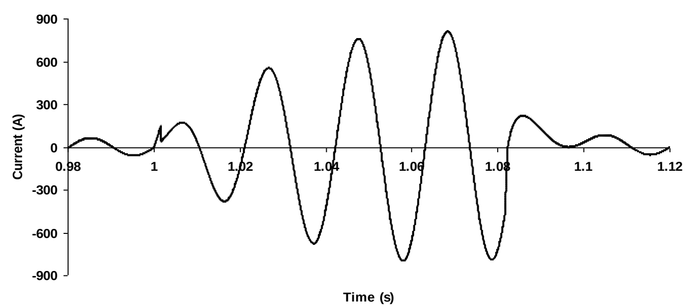

Fig. 9. Line current without using arrester in the proposed structure

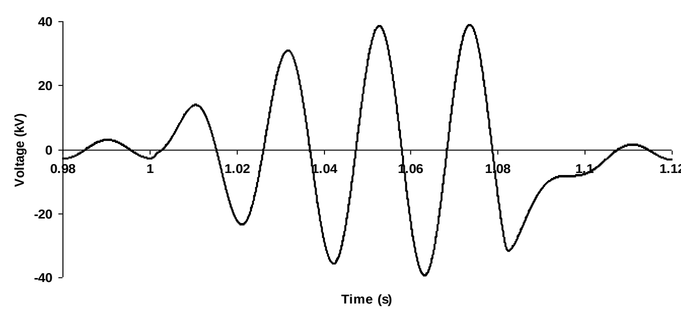

Fig. 10. Capacitor voltage without using arrester in the proposed structure

V. CONCLUSION

A new topology for FCL based on series LC resonance circuit is introduced in this paper. Analytic analysis for the proposed structure is performed carefully and simulations are presented using PSCAD/EMTDC software. This structure can limit the fault current level to a constant value and prevents its increasing variation. It has high speed and low cost because of using self turn off switch and non-superconducting inductor. In addition, capacitor of this FCL can be used as a series compensator. In general, the proposed structure has good capability for fault current limiting.

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